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The evaluation of the long-term drift of electrical capacitance measurement standards by two methods

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Abstract

Measurements of electrical capacitance are essential in various fields of electrical engineering, electronics and other fields. Capacitance measurements are necessary for correct design of electrical circuits and devices. Such measurements help ensure the stability and reliability of electrical systems such as power supplies, filters, capacitors, etc. In some applications, such as radio transmitters, filters, and other electronic devices, it is needed to maintain certain frequency characteristics.

It is critical and appropriate to consider various factors related to the drift of the measuring instrument or measurement standard when performing measurements to ensure the required accuracy and reliability of the measurements. The study of the time drift of the measurement standard is mandatory when carrying out comparisons of national measurement standards. The types of the drift and main methods of its evaluation for measuring instruments and measurement standards between their calibrations were analysed.

A conventional method of the long-term drift analysis involves the use of regression models followed by their detailed analysis. Such models are specific mathematical functions that describe theoretical values that best represent the underlying bias in the time series for the long-term drift. Exponentially Weighted Moving Average (EWMA) charts reduces the lag inherent in conventional moving averages by giving more weight to recent observations.

The results of the evaluation of the long-term drift of measurement standards of electrical capacitance for high-precision calibration of measurement standards by polynomial regression diagrams and EWMA charts are given. Polynomials of the 2nd degree were sufficient to approximate the drift of electrical capacitance measurement standards under consideration. The application of EWMA charts showed greater sensitivity to drift changes over the past few years of observations compared to the regression analysis. Consistent results were obtained.

Keywords: long-term drift; capacitance measurement standard; measurement uncertainty; polynomial regression; Exponential Weighted Moving Average.

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Introduction

Measurements of electrical capacitance are essential in various fields of electrical engineering, electronics and other fields. Capacitance measurements are necessary for correct design of electrical circuits and devices. Such measurements help ensure the stability and reliability of electrical systems such as power supplies, filters, capacitors, etc. In some applications, such as radio transmitters, filters, and other electronic devices, it is needed to maintain certain frequency characteristics. In research projects, high-precision capacitance measurements are an integral part of developing new technologies, improving existing devices, and solving specific tasks [1–5].

The instrumental drift of a measuring instrument is characterized by a continuous or gradual change in readings over time due to a change in metrological characteristics of the properties of the instrument or a measurement standard [6]. It is related neither to a change in the quantity being measured nor to a change in any recognized influence quantity, and applies both to the measuring instrument and to the measurement standard [7, 8]. A drift line is a line along which points representing data from a certain time series of data are located on the graph.

It is critical and appropriate to consider various factors related to the drift of the measuring instrument or measurement standard when performing measurements to ensure the required accuracy and reliability of the measurements. The study of the time drift of the used measurement standard is mandatory when carrying out comparisons of national measurement standards. Accurately accounting for the drift helps maintain measurement accuracy, while unaccounted drift can lead to significant measurement uncertainties. To establish and change calibration intervals for measurement standards and measuring instruments, the long-term drift shall be mandatory evaluated. A standard drift is one of the components of the combined measurement uncertainty, so accounting for it helps improve measurement accuracy [9].

The weight of the value in the Exponential Weighted Moving Average (EWMA) chart decreases exponentially for each subsequent period in the past. The EWMA value contains a pre-calculated average, meaning that the calculated result becomes cumulative. All received data contribute to the result, but this contribution is reduced when calculating the next period of the EWMA chart [10, 11].

Evaluation of the drift of measurement standards between calibrations

The ordinary least squares method (OLS) cannot be used to reliably estimate calibration results, since it makes sense only under certain conditions [12], so it is not used further in the paper. Such conditions can be:

• absence of uncertainty associated with x (measurement uncertainties always arise during calibration);

• the measurement uncertainty is constant over the entire measurement range (this rarely occurs during calibration);

• there is no covariance between $x_i(t)$ and $y_i(t)$ (these deviations are often encountered during calibration).

At the same time, the least squares method in some cases can be used to estimate calibration intervals.

In [12] it is proposed to consider the established corrections to account for the real deviation, as well as the average value and standard deviation of the received corrections to evaluate the drift of a measurement standard or measuring instrument. These characteristics reflect the contribution of the instrumental drift to the measurement uncertainty.

The instrumental drift of measuring instruments or measurement standards is identified in [13]. In this case, both systematic and random drift are distinguished. Due to systematic drift over time, the model that establishes the relationship between the measured and "true" values changes. The deviation of the selected model and obtained real values during the calibration process is characterized by random drift.

The calibration model often takes the form of a polynomial regression of appropriate degree n (usually 1, 2 or 3) and is used to describe the relationship between the values of $y(t)$ and $x(t)$:

$$y(t) = a_0 + \sum_{i=1}^{n} a_i x^i(t), \qquad (1)$$

where $a_i\,(i = 0, 1, \ldots, n)$ is some number; $x^i(t)$ is the value of the input value in degree i $(i = 1, \ldots, n)$.

A general method of optimization and justification of calibration intervals of measuring instruments or measurement standards is proposed in [14]. It is necessary to account for the changes in metrological characteristics of measurement standards and measuring instruments to ensure the optimization and justification of their established calibration intervals for a particular laboratory. It is also necessary to consider the contribution of the used measurement standards and measuring instruments to the evaluation of combined measurement uncertainty for real measurement conditions.

The long-term drift of measurement standards is considered in [15] which is also recommended in the international standard IEC/ISO 17025 [9] and the JCGM 100 guide [16]. Control charts with simulations and real data packages are presented and validated. Time series analysis using EWMA charts may be more appropriate than conventional control charts. Autocorrelation of measurement data over long periods of time limits the relevance of control charts.

The algorithm for random drift of metrological characteristics of measuring instruments is described in [17]. An overview of methods for considering the drift of measurement standards and measuring instruments, implying the use of calibration data of measuring instruments is given. Analysis of such methods is useful in establishing necessary statistical characteristics to evaluate the drift. Such characteristics make it possible to predict possible drift of a measurement standard or measuring instrument. This allows making all the necessary adjustments when receiving measurement results.

A method of correlation evaluation of the deviation drift in time is presented in [18]. The method is based on the analysis of the sample and the calculation of the standard deviation to obtain a corresponding unbiased maximum mean. If the deviation drift is greater than the unbiased maximum mean, then it is considered to have a strong time correlation. In another case, the deviation drift is considered to have no time correlation, so part of the deviation drift can be ignored when calculating the amount of drift.

In [19], a method for considering the time drift is proposed, which is based on the requirements of the JCGM 100 guide [16]. A linear regression of the resulting measurement data can be used to evaluate additional components of the combined measurement uncertainty. Options for evaluating the measurement uncertainty of the drift after calibration of measuring instruments are suggested. A single value for the combined measurement uncertainty within the calibration interval can be obtained based on the application of the proposed methods.

In general, the contribution of the time drift to the combined measurement uncertainty of a fine calibration cannot be averaged over a series of measurements because the characteristics of such drift may not be sufficiently stable. A method for suppressing parasitic effects during a slow drift is presented in [20]. The effectiveness of this method is illustrated by applying the resulting optimal strategies to some precision measurements.

The ability to compare obtained measurement results and assess temporal changes in the combined measurement uncertainty is limited for evaluation of the accuracy and precision of laboratory measurements. Correcting the drift estimate and establishing assumptions for users to evaluate measurement uncertainty is an important component for evaluating the calibration results of measuring instruments and measurement standards [21].

Evaluation of the drift of electrical capacitance measurement standards for calibrations using two methods

A conventional method of the long-term drift analysis involves the use of regression models followed by their detailed analysis. Such models are specific mathematical functions that describe the theoretical values that best represent the underlying bias in the time series for the long-term drift [7, 8].

The coefficient of determination R^2 is conventionally used when evaluating the accuracy of a drift line model in the form of a polynomial regression:

$$R^2 = \sigma_{\hat{y}}^2 / \sigma_y^2, \qquad (2)$$

where $\sigma_{\hat{y}}$ and σ_y are dispersions of theoretical data obtained according to the drift model and empirical calibration data, respectively.

The most reliable and adequate approximation of the drift line to the investigated process in time is if the value of its coefficient of determination is equal to or close to 1. In the key and additional reconciliations of national measurement standards of electric capacity, only linear regression was used to describe the drift line of transfer measurement standards.

A new accurate capacitance measurement method using an Ultra-Precision Capacitance Bridges is described in [22]. The measurement results of the capacitance measurement standards of 10 pF and 100 pF at frequencies of 1 kHz and 1.592 kHz, obtained using the proposed method, were compared with the measurement results obtained using a conventional substitution method. The measurement uncertainty for a capacitance measurement standard of 10 pF was 4.3 μF/F, and for a capacitance measurement standard of 100 pF it was 4.4 μF/F at a frequency of 1 kHz. The drift of the used measurement standard for 100 pF was evaluated as 0.11 (μF/F)/year.

Ukrainian national measurement standards of electrical capacitance units were established at the SE "Ukrmetrteststandard" (Kyiv, Ukraine) in 2009 and used for precision calibrations of working electrical capacitance measurement standards. Those measurement standards took part in comparisons of national measurement standards within the framework of regional metrology organizations from 2009 to 2017 [23–27]. Time series of measurement data of the capacitance measurement standard are available from 2011 to 2022.

The capacitance measurement Andeen-Hagerling model AH11A of 10 pF (no. 01327) and 100 pF (no. 01328) are reference measures for national metrological traceability for electric capacitance measurements which have drift not more than 0.3 ppm/year [23–27]. Long-term drifts of the specified reference measures are evaluated by a 2[nd] order polynomial and are shown in Figs 1 and 2. In the figures, the green solid line is the average drift value, the red dotted line is the polynomial approximation of the measure drift. The R^2 values for these capacitance measures are 0.12 and 0.70, respectively. They confirm the adequacy of the obtained polynomial approximations.

The measure of 10 pF has an average value of 10.000005 pF, and the measure of 100 pF has an average value of 100.00007 pF. The difference between the maximum and minimum values of both specified measures does not exceed 0.8 ppm. The difference between the first and last values for both measures is 0. Both measures are in the same constructive case and had unexplained anomalous values in 2018.

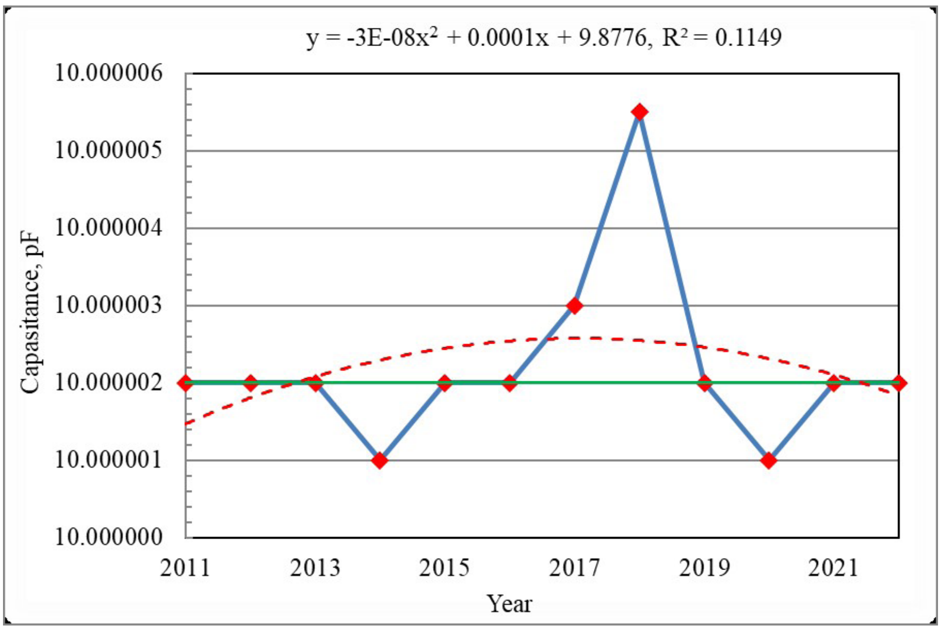

Fig. 1. Capacitance measure of 10 pF drift from 2011 to 2022

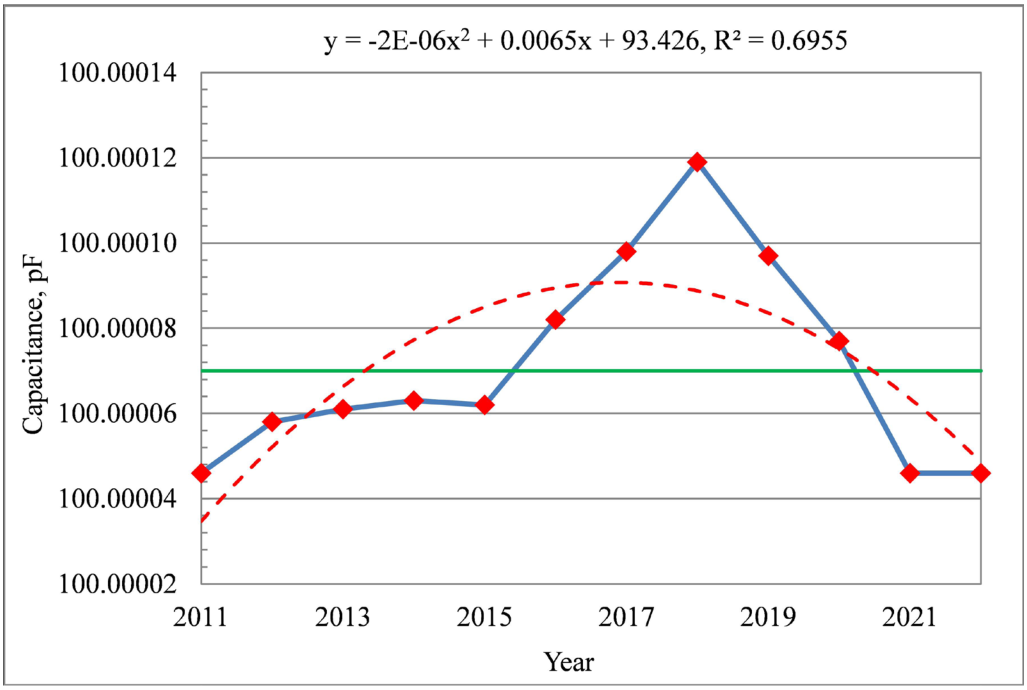

Fig. 2. Capacitance measure of 100 pF drift from 2011 to 2022

Also, anomalous values of both measures were recorded during comparisons in 2009 [25, 26].

The EWMA method uses an exponentially weighted moving average derived from a time series of data. The obtained value using this method has a cumulative value. The weight of this estimation decreases exponentially compared to each previous period. The EWMA method can be a good tool for capturing small bias in average values over time. This makes it possible to obtain and analyze the long-term drift of metrological characteristics of measurement standards or measuring instruments [10].

The EWMA statistic at time t is calculated recursively from the individual data points for data Y_1, Y_2, ..., Y_t. The first $EWMA_1$ statistic is the arithmetic average of historical data. The EWMA chart can be sensitive to small drift by the choice of the special weighting factor λ:

$$EWMA_{t+1} = \lambda Y_t + (1-\lambda) EWMA_t. \quad (3)$$

The usual range of values for factor λ is from 0.2 to 0.3 [10].

The centre line (CL) of the EWMA chart represents the average of the historical data. The up-

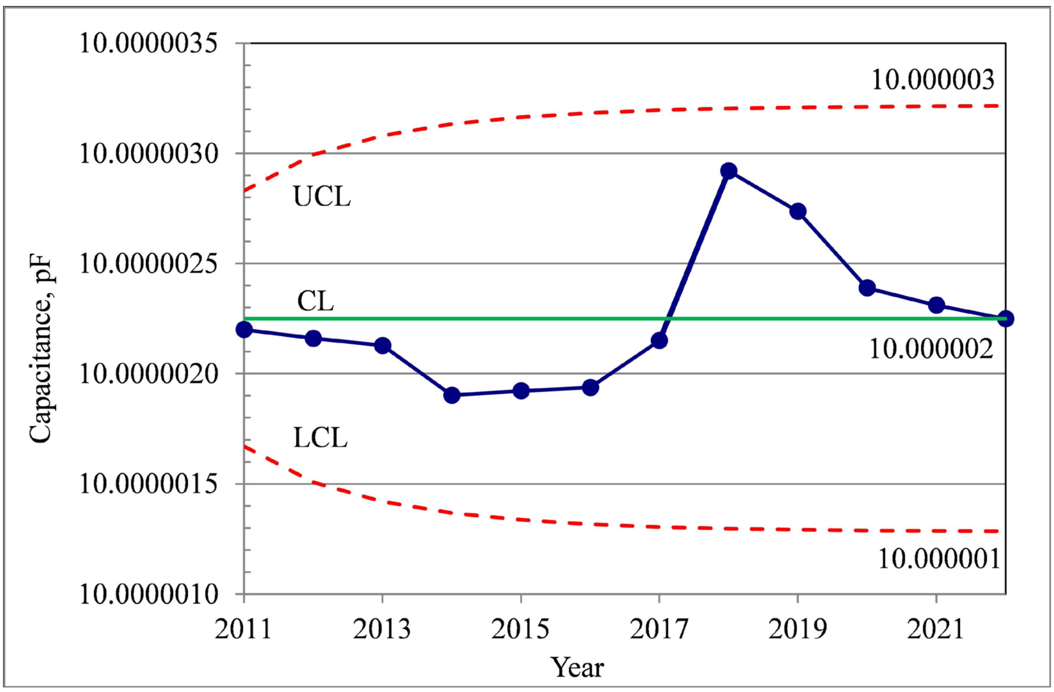

Fig. 3. Drift for measure of 10 pF with EWMA from 2011 to 2022

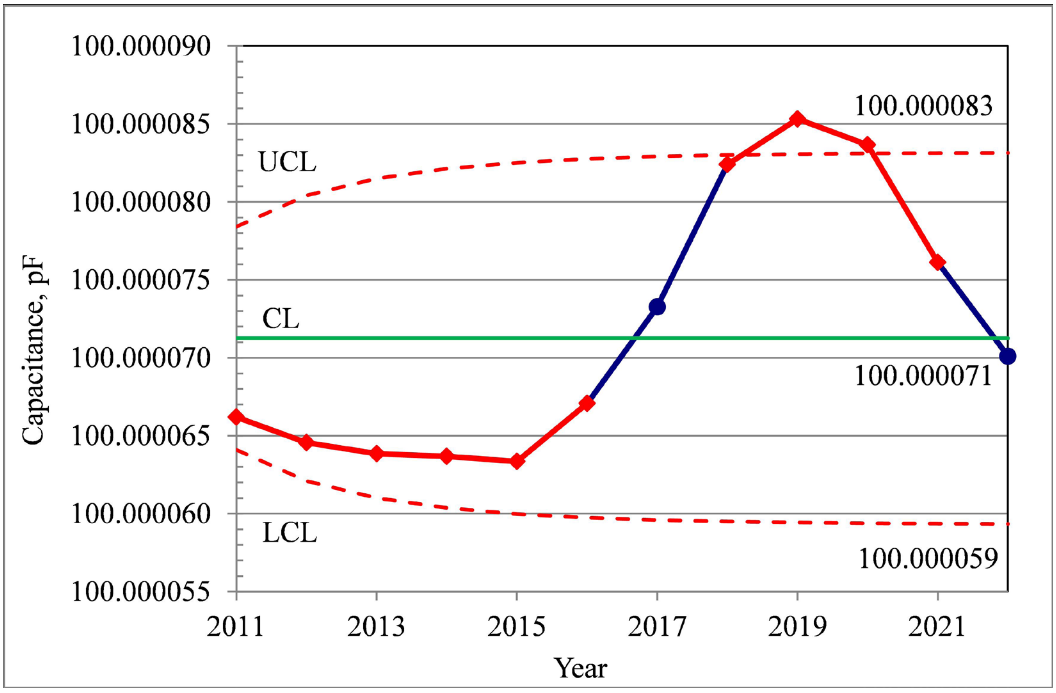

Fig. 4. Drift for measure of 100 pF with EWMA from 2011 to 2022

per (UCL) and lower (LCL) limits are determined by the expressions:

$$\text{UCL} = EWMA_1 + ks\sqrt{\frac{\lambda}{(2-\lambda)}}, \quad (4)$$

$$\text{LCL} = EWMA_1 - ks\sqrt{\frac{\lambda}{(2-\lambda)}}, \quad (5)$$

where k is a multiplicative factor which is usually chosen to be 2 or 3, and s is a standard deviation of the historical data. The function under the radical is a good approximation to the component of the standard deviation of the EWMA statistic that is a function of time.

The evaluation results of the long-term drift of a capacitance measurement standard of 10 pF and 100 pF at a frequency of 1 kHz using the EWMA are shown in Figs 3 and 4 (k=3, λ=0.2). In the figures, the green solid line is the average drift value – CL, the red dotted line is UCL or LCL chart limits. The last points of the diagrams on those figures for both capacitance measures are within the calculated control limits.

For measure of 10 pF, the average drift value is 10.000002 pF, and for measure of 100 pF, it is 100.000071 pF. The UCL and LCL values for the measure of 10 pF are 10.000003 pF and 10.000001 pF, and for the measure of 100 pF – 100.000083 pF and 100.000059 pF, respectively. The measure of 10 pF values is completely within controllable limits, and the measure of 100 pF values are almost all within controllable limits.

Summary

Regression analysis methods are most often used to evaluate the drift of almost all electrical measures, in particular capacitance measures, which are used in the calibration of measuring instruments. The EWMA reduces the lag inherent in conventional moving averages by giving more weight to recent observations. Therefore, the EWMA chart was chosen to further analyse a very small long-term drift of high-precision capacitance measurement standards.

Polynomial regression and the EWMA charts were used to evaluate the drift of electrical capacitance measurement standards for high-precision calibrations. The EWMA statistics are weighted averages, so their standard deviations are smaller than the standard deviations of the raw data. Polynomials of the 2nd degree were sufficient to approximate the drift of the electrical capacitance measurement standards under consideration. Consistent results were obtained. The application of the EWMA charts showed greater sensitivity to the drift changes over the past few years of observations compared to the regression analysis.

Simultaneous use of the regression analysis method and EWMA can be useful for levelling the shortcomings of each method. This allows considering the detected changes in the process of calibration of other measures or measuring instruments.

Оцінювання довгострокового дрейфу еталонів електричної ємності двома методами

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Анотація

Вимірювання електричної ємності важливі в різних галузях електротехніки, електроніки та інших сферах. Вимірювання ємності необхідні для правильного проєктування електричних ланцюгів і пристроїв. Такі вимірювання допомагають забезпечити стабільність і надійність електричних систем, таких як джерела живлення, фільтри, конденсатори тощо. У деяких програмах, таких як радіопередавачі, фільтри та інші електронні пристрої, важливо підтримувати певні частотні характеристики.

Для забезпечення необхідної точності та надійності вимірювань важливо та доцільно враховувати різноманітні фактори, пов'язані з дрейфом вимірювального приладу або еталона. Дослідження дрейфу еталона в часі є обов'язковим при проведенні звірень національних еталонів. Оцінка довгострокового дрейфу є обов'язковою для встановлення інтервалів калібрування. Проведено аналіз видів дрейфу та основних методів його оцінки для засобів вимірювань і еталонів між їх калібруваннями.

Традиційний метод аналізу довгострокового дрейфу передбачає використання регресійних моделей із наступним їх детальним аналізом. Така модель є конкретною математичною функцією, що описує теоретичні значення, які найкраще демонструють основний зсув у часовому ряді для довгострокового дрейфу. Графіки експоненційного зваженого ковзного середнього (EWMA) зменшують відставання, властиве традиційним ковзним середнім, надаючи більшої ваги останнім спостереженням.

Наведено результати оцінки довготривалого дрейфу еталонів електричної ємності для високоточного калібрування еталонів із використанням поліноміальної регресії та діаграм EWMA. Поліномів 2-го ступеня було достатньо для апроксимації дрейфу досліджуваних еталонів електричної ємності. Застосування діаграм EWMA показало більшу чутливість до змін дрейфу в останні роки спостережень порівняно з регресійним аналізом. Були отримані послідовні результати.

Ключові слова: довгостроковий дрейф; еталон електричної ємності; невизначеність вимірювання; поліноміальна регресія; експоненційне зважене ковзне середнє.

References

1. Wajman R. et al. Spatial imaging with 3D capacitance measurements. *Measurement Science and Technology*, 2006, vol. 17, no. 8, p. 2113. doi: https://doi.org/10.1088/0957-0233/17/8/009
2. Dimitrios K. Kampouris et al. A new approach for the improved interpretation of capacitance measurements for materials utilised in energy storage. *RSC Advances*, 2015, no. 5, pp. 12782–12791. doi: https://doi.org/10.1039/C4RA17132B
3. Huber H.P. et al. Calibrated nanoscale capacitance measurements using a scanning microwave microscope. *Rev. Sci. Instrum.*, 2010, vol. 81, p. 113701. doi: https://doi.org/10.1063/1.3491926
4. S.L.M. van Mensfoort, R. Coehoorn. Determination of Injection Barriers in Organic Semiconductor Devices from Capacitance Measurements. *Phys. Rev. Lett.*, 2008, vol. 100, 086802. doi: https://doi.org/10.1103/PhysRevLett.100.086802
5. Vendrame L., Bortesi L., Cattane F., Bogliolo A. Crosstalk-based capacitance measurements: theory and applications. *IEEE Transactions on Semiconductor Manufacturing*, 2006, vol. 19, issue 1, pp. 67–77. doi: https://doi.org/10.1109/TSM.2005.863263
6. JCGM 200:2012. International vocabulary of metrology – Basic and general concepts and associated terms (VIM). 3rd edition. 2012. 108 p.
7. Velychko O., Gordiyenko T. Evaluation of the long-term drift of measuring instruments and standards using time series. *26th IMEKO TC4 International Symposium and 24th International Workshop on ADC/DAC Modelling and Testing* (IWADC), Pordenone, Italy, 2023, pp. 1–5. doi: https://doi.org/10.21014/tc4-2023.01
8. Velychko O., Gordiyenko T. Estimating the long-term drift of travelling measurement standards for comparisons. *Ukrainian Metrological Journal*, 2023, no. 4, pp. 9–15. doi: https://doi.org/10.24027/2306-7039.4.2023.298632
9. ISO/IEC 17025:2017. General requirements for the competence of testing and calibration laboratories. 2017. 30 p.

10. NIST/SEMATECH. e-Handbook of Statistical Methods. NIST, 2006. Available at: https://www.itl.nist.gov/div898/handbook/
11. ISO 7870-6:2016. Control charts. Part 6: EWMA control charts. 2016. 32 p. Available at: https://icontec.isolutions.iso.org/ru/standard/40173.html
12. Jones L.A., Champ C.W., Rigdon S.E. The Performance of Exponentially Weighted Moving Average Charts with Estimated Parameters. *Technometrics*, 2001, vol. 43, issue 2, pp. 156–167. doi: https://doi.org/10.1198/004017001750386279
13. Pou J.-M., Leblond L. Evaluate and quantify the drift of a measuring instrument. *Proc. of 19th Intern. Congress of Metrology*, 2019, 12004, 13 p. doi: https://doi.org/10.1051/metrology/201912004
14. FD X 07-014:2006. Metrology – Optimisation of measuring equipment calibration frequencies. AFNOR, 2006. Available at: https://pdfcoffee.com/norme-periodicite-pdf-free.html
15. Romain C. Evaluation of the Long-Term Stability of Metrology Instruments. *Applied Aspects of Modern Metrology*. IntechOpen. 2022. doi: https://doi.org/10.5772/intechopen.100511
16. JCGM 100:2008. Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM). 134 p.
17. Luo G. et al. Analysis and Research Based on Instrument Drift Data. *IEEE Access*, 2021, vol. 9, pp. 56915–56926. doi: https://doi.org/10.1109/ACCESS.2021.3071883
18. Sikström S., Jönsson F. A Model for Stochastic Drift in Memory Strength to Account for Judgments of Learning. *Psychological Review*, 2005, vol. 112, no. 4, pp. 932–950. doi: https://doi.org/10.1037/0033-295X.112.4.932
19. Delker C.J. et al. Calculating Interval Uncertainties for Calibration Standards that Drift with Time. *NCSLI Measure*, 2018, vol. 12, no. 4, pp. 9–20. doi: https://doi.org/10.1080/19315775.2020.1774945
20. Yashchuk V.V. Optimal measurement strategies for effective suppression of drift errors. *Rev Sci Instrum.*, 2009, vol. 80, issue 11, 115101. doi: https://doi.org/10.1063/1.3249559
21. Csavina J. et al. Traceable measurements and calibration: a primer on uncertainty analysis. *Ecosphere*, 2017, vol. 8, issue 2, 01683. doi: https://doi.org/10.1002/ecs2.1683
22. Hamed H.A.M. et al. New proposed method for traceability dissemination of capacitance measurements. *International Journal of Electrical and Computer Engineering (IJECE)*, 2021, vol. 11, no. 3, pp. 1969–1975. doi: http://doi.org/10.11591/ijece.v11i3.pp1969-1975
23. Jeffery A.-M. Final report on key comparison CCEM-K4 of 10 pF capacitance standards. *Metrologia*, 2002, vol. 39(1A):01003. doi: 10.1088/0026-1394/39/1A/3
24. Belliss J.H. International comparison of 10 pF and 100 pF capacitance standards: EUROMET Project No. 345. *Metrologia*, 2000, vol. 37, no. 4. doi: 10.1088/0026-1394/37/4/8
25. Velychko O., Akhmadov O. Final report on COOMET key comparison of capacitance at 10 pF (COOMET.EM-K4). *Metrologia*, 2017, vol. 54(1A):01005. doi: 10.1088/0026-1394/54/1A/01005
26. Velychko O., Akhmadov O. Final report on COOMET key comparison of capacitance at 100 pF (COOMET.EM-S4). *Metrologia*, 2017, vol. 54(1A):01006. doi: 10.1088/0026-1394/54/1A/01006
27. Velychko O., Shevkun S. Final report on COOMET supplementary comparison of inductance at 10 mH and 100 mH at 1 kHz (COOMET.EM-S14). *Metrologia*, 2016, vol. 53(1A), 01009. doi: https://doi.org/10.1088/0026-1394/53/1A/01009